B.S.T.J. BRIEFS

Modulation of Laser Beams by Atmospheric Turbulence

By M. SUBRAMANIAN and J. A. COLLINSON

(Manuscript received January 11, 1965)

When laser beams are propagated through the air, they are modulated with a noise-like spectrum[1,2] having a baseband width the order of hundreds of cycles and a nearly exponential frequency distribution.[1] Hogg[1] used a 2.6-km path; Hinchman and Buck[2] used paths of 9 and 90 miles. In each case the optics and range were such that the receiver collected a small fraction of the total beam. Since atmospheric refraction causes twinkling and tearing of the beam, one would expect amplitude modulation of the signal received under these conditions even for constant intensity of the total beam.

We report here that the shape of the noise spectrum is unchanged when all of the detectable beam is received. Moreover, the spectrum is unaffected by changes in the diameter or geometrical divergence of the transmitted beam, by whether the receiver is in the near or far field of the transmitter, or by a threefold change in transmission distance. The general spectrum characteristics appear to be determined by atmospheric conditions.

We have transmitted a horizontally polarized 6328-Å laser beam over a 120-meter path 8 meters above black-top pavement. The beam was detected through a 3Å-wide interference filter by an RCA 7265 photomultiplier tube. The frequency spectrum of the signal was analyzed and displayed on a CRT by a Singer Metrics TA-2 spectrum analyzer. The resolution of the analyzer was 70 cycles, and its low frequency limit was 20 cycles. Each spectral analysis took one second. Generally, 120 successive spectral patterns were recorded, and thus averaged, in a single photograph of the CRT screen. The laser[3] oscillated in a single transverse and axial mode and provided about one milliwatt of power in a diffraction-limited Gaussian beam one millimeter in diameter. Measurements were taken with the direct beam, so that the receiver was very much in the far field of the transmitter. Telescopes of 9, 20, and 38 powers were used to enlarge the diameter of the transmitted beam, reduce diffraction spreading, and put the receiver in the near field. The telescopes were focused to vary the geometrical beam divergence, or convergence, thus greatly varying the size of the received beam. With the 38-power tele-

scope focused on the receiver, the beam diameter was 4 cm as transmitted, about 1 cm as received. The fraction of the total beam collected varied from one to much less than one with these variations in the transmitter. In no case did any of these changes produce a detectable change in the spectrum.

To investigate more carefully the effect of collecting part of the beam, the beam was transmitted plane parallel and 2 cm in diameter, diverging to 3 cm as received. (No signal above shot noise could be found beyond a 3-cm diameter.) An iris was placed before the receiver, and its diameter was adjusted from 4 to 1 cm, again with no effect on the spectrum.

To assess the possibility that the noise spectrum is produced by the product of the sensitivity profile of the photocathode by the time-varying intensity profile of the beam, a 4-inch, diffraction-limited lens was used at the receiver to focus the beam to a spot about one millimeter in diameter. (One millimeter is smaller than the scale of the structure of the photocathode sensitivity.) The spectrum was unchanged from that with no lens.

The effect of transmission distance was observed by splitting the beam at the receiving station, returning (with a corner reflector) part to the transmitting station and (with a flat mirror) reflecting that part again to the receiving station. Thus there were available to the receiver two beams, otherwise similar, which had traversed 120 m and 360 m of air. When the beams were switched on the receiver alternately with successive one-second scans by the analyzer, no change in the spectrum was seen. This was true at different times and under different conditions. Table I summarizes only the single most extensive run, lasting 5 hours and including thousands of individual spectra. The data entered are the widths, in cycles per second, from the maximum (at the 20-cycle cutoff of the analyzer) to the reduction from maximum shown. It is readily seen that there is no significant effect of distance on spectral width. Indeed, the agreement seems surprisingly good in view of the errors listed. The reason is that the errors are mean deviations of spectra which changed steadily over 5 hours, the spectra for the two distances changing together.

Table I — Shape of Spectrum at Two Distances

Distance	Width of Spectrum			
	Power level below 20-cycle peak by			
	$-2\frac{1}{2}$ db	-5 db	$-7\frac{1}{2}$ db	-10 db
120 meters	39 ± 8 cps	84 ± 14 cps	126 ± 19 cps	176 ± 25 cps
360 meters	38 ± 10	82 ± 22	124 ± 29	168 ± 40

This change in spectra correlated with changes in atmospheric conditions. As conditions changed in a pronounced way from one day to the next, so too did the spectra change in a pronounced way. Noise spectra obtained under five widely different weather conditions are plotted in Fig. 1. The curves are of the form $P(f) = \text{const} \exp(-\alpha f)$, and the value of α accompanies each curve. $P(f)$ is relative modulated power in the beam, and f is frequency. The data for curve A were obtained at 6:30 a.m. under an overcast sky. Thus the ground had cooled overnight and had not yet been warmed by the morning sun. Although a steady 10-mph wind was blowing, this was by far the narrowest spectrum observed. For B, the wind was steady, and there was sun on the pavement. For C, the wind was gusty, but there was no sun. For D, the wind was gusty, and there was sun. For E, the wind was violently gusty and there was heavy rain. The departure from exponential dependence probably was caused by the rain.

It appears that the spectrum is broadened to the extent that atmospheric conditions produce refractive gradients along the path. While the other variables may have affected the amplitude of the spectrum, they did not alter the shape. We are further investigating the effect of range, since at zero distance the amplitude is known to reduce to zero.

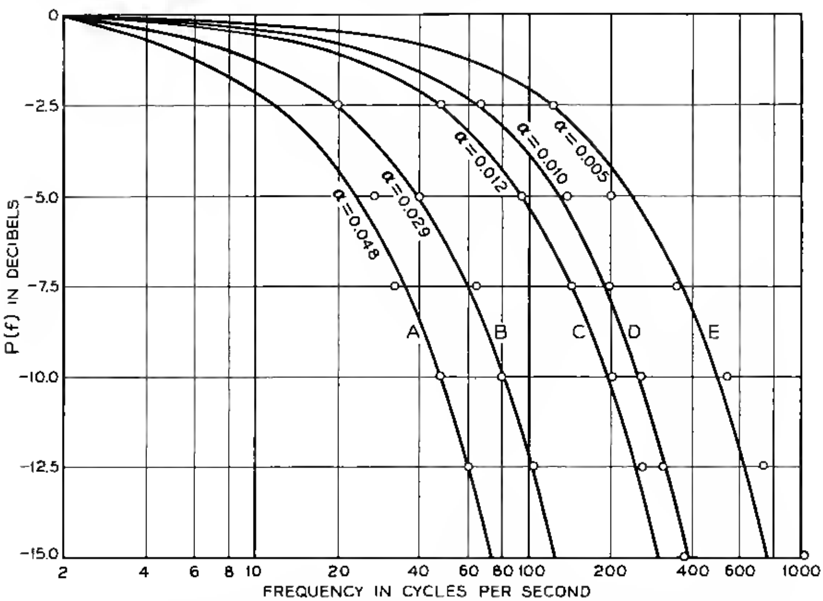

Fig. 1 — Dependence of the modulation spectrum on weather conditions. Refractive gradients increase from curve A to curve E as described in text.

The dependence of both spectral width and per cent modulation on range are of particular interest from a theoretical point of view. Spectral width should be independent of distance in the single-scatter regime, and per cent modulation should be small. The extent of the single-scatter regime depends upon the scale size of the refractive structure and upon the amplitude of variations in the refractive index. More extensive measurements are being made to allow a definitive comparison of theoretical expectations with the observations.

REFERENCES

1. Hogg, D. C., On the Spectrum of Optical Waves Propagated through the Atmosphere, B.S.T.J., *42*, Nov., 1963, pp. 2967–2969.
2. Hinchman, W. R., and Buck, A. L., Fluctuations in a Laser Beam over 9- and 90-Mile Paths, Proc. IEEE, *52*, March, 1964, pp. 305–306.
3. This is a single-frequency RF-excited laser to be described in a forthcoming publication by J. A. Collinson.